On the analysis of hydrocarbon leaks in the Norwegian offshore industry

Jan Erik Vinnem*

University of Stavanger/Preventor AS, Norway

A B S T R A C T

There have been several major offshore accidents in different offshore regions since 2005. In Norway there have been several very serious near-misses during the last ten years, several of which involving serious hydrocarbon leaks with catastrophic fire and explosion potential. All these severe occurrences demonstrate the importance of learning from major accident precursors in order to appraise the risk potential involved in critical offshore operations. This paper is based on analysis of about 175 hydro-carbon leaks in the period 2001-2010. Regulatory requirements in Norway are aimed at preventing as far as possible such occurrences during night time, but the analysis shows that this has been far from successful. The industry has for many years claimed that the maintenance personnel are the main group of employees involved in causing these leaks. This study has shown that leaks during the execution of maintenance and modification are less than half of the leaks, and that failures during the preparation for carrying out maintenance tasks are more frequent. Such preparations have often been conducted during night shift. The analysis gives a strong incentive to change this practice.

1. Introduction

It has been demonstrated over the last ten years that personnel involved in process system interventions are involved in the causation of more than half of the leaks (96 out of 175, see Fig. 2) from process plants of offshore installations in the Norwegian sector (Vinnem, Seljelid, Haugen, & Husebø, 2007). The leaks in question are those with escalation potential, and a mix of gas, condensate and crude oil leaks, see further details in Section 2. Competence, attitudes, motivation and other relevant factors would therefore influence the performance of interventions and the associated probability of leaks as well as the performance of Emergency Shutdown (ESD) valve maintenance. This is discussed in some depth by Vinnem, Hestad, Kvaløy, and Skogdalen (2010).

Major accidents are rare in offshore operations, the last major accident, at least with fatalities, in offshore operations on the Norwegian continental shelf occurred in 1985. Even precursor events are quite rare, typically in the order of one event per installation per year. It is therefore crucially important to maintain motivation and awareness in order to prevent as far as possible the occurrence of such precursor events. The next precursor event may be the next major accident if the battery of mitigation barriers on offshore installations has a complete failure.

Major hazard precursor events can be many types of events, such as vessels on collision course, structural defect, temporary loss of well control as well as Okstad, Jersin, and Tinmannsvik (2012) has analyzed 25 accident and incident investigations, and has focused on causal factors. It is also pointed out that the investigation process should be improved. They also observe that with the exception of one case, the accident potential of the different accidents was more comprehensive than actually occurred, but it should be noted that only 5 hydrocarbon leaks were included in the study of Okstad et al. (2012).

Thunem, Kaarstad, and Thunem (2009) has analyzed 20 investigation reports in the Norwegian petroleum industry, and has documented that the consideration of organizational factors in accident investigations is unsystematic due to lack of consensus and common understanding about which organizational aspects to consider. One weakness of Okstad et al. (2012) and Thunem et al.(2009) is that no distinction is made between occupational acci-dents and major accident precursors. This is discussed further in Section 5.1.

Kongsvik, Johnsen, and Sklet (2011) has explored the extent to which a safety climate measure from a survey on working conditions used in an oil and gas company can be used as a leading and lagging indicator in relation to hydrocarbon leaks on offshore

Abbreviations: CCR, Central Control Room; ESD, Emergency shutdown; HSE, Health and Safety Executive; MTO, Man, Technology and Organisation; NCS, Norwegian Continental Shelf; NTNU, Norwegian University of Science and Technology; PSA, Petroleum Safety Authority; RIF, Risk Influencing Factor; WP, Work Permit.

* Tel.: +47 51487880; fax: +47 51487881.
E-mail address: jev@preventor.no.

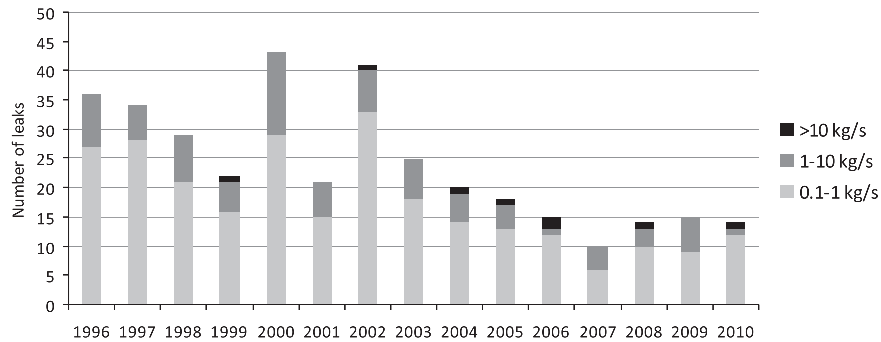

Fig. 1. Hydrocarbon leaks on Norwegian continental shelf, 1996-2010 (n = 357, PSA, 2011a).

installations. It was found that the safety climate measure could serve as both a leading and lagging indicator for hydrocarbon leaks, based on the empirical evidence in the study.

SINTEF has on behalf of the Petroleum Safety Authority analyzed a selection of the leaks on the Norwegian Continental Shelf (NCS) in the period 2002e2009 (2011b), but has not used a work process model for the analysis of leaks. As a consequence, the different personnel groups are also not considered. Their conclusions are distinctly different from all other works on the causes of leaks (Haugen, Vinnem, & Seljelid, 2011; Sklet et al. (2010), in the sense that aspects associated with design are found to be the main cause category of hydrocarbon leaks.

When it comes to details of circumstances of such leaks, we find only to a limited extent such information published. UK Health and Safety Executive (HSE) has published annual reports on the hydrocarbon leaks reported from the UK offshore industry, but has not focused on work process modelling. Petroleum Safety Authority (PSA) [Norway] has also published annual statistics; see Fig. 1.

Edmondson (2004) has published a paper on the experience of HSE, and its campaign to reduce the number of leaks by 50%. Edmondson notes that causes are not associated with great technical complexity, but often failures in basic controls and proce-dures. This is in line with the findings previously by this author, and the main message of the present paper. The most recent study of leaks reported to HSE is Li (2011), which confirms the previous analysis. Circumstances of the leaks in the Norwegian sector have been analyzed in some depth by Haugen et al. (2011) for the period 2001e2009.

A risk analysis model (Risk_OMT model) for detailed analysis of circumstances of hydrocarbon leaks have been developed by Vinnem et al. (2012), a discussion of the use of the model is provided by Gran et al. (2012).

The objective of the paper is to study details about the hydrocarbon leaks from the investigations, in order to find particularities about these precursors that may help to understand why it is a high frequency of leaks. The leaks are analyzed on the basis of the work process model developed by the Risk_OMT project. This is a theoretical model which has not been calibrated against operational experience. The present paper is the first opportunity to present data for the parameters in the model. The present study gives a unique insight into detailed information about circumstances of leaks that have not been publically available before. The study is also unique with respect to the large amount of data that is avail-able, i.e. the number of leaks and the high percentage of investigations.

Chapter 2 gives an overview of the hydrocarbon leaks and associated trends. Chapter 3 presents an analysis of the leaks in a work process context, whereas Chapter 4 discusses the times at which the leaks occur. The findings are discussed in Chapter 5, followed by conclusions in Chapter 6.

2. Overview of major accident precursor events

The development of the number of leaks per year is documented by Petroleum Safety Authority in the RNNP report (PSA, 2011a). Fig. 1 presents the overall trends in the period 1996e2010. The

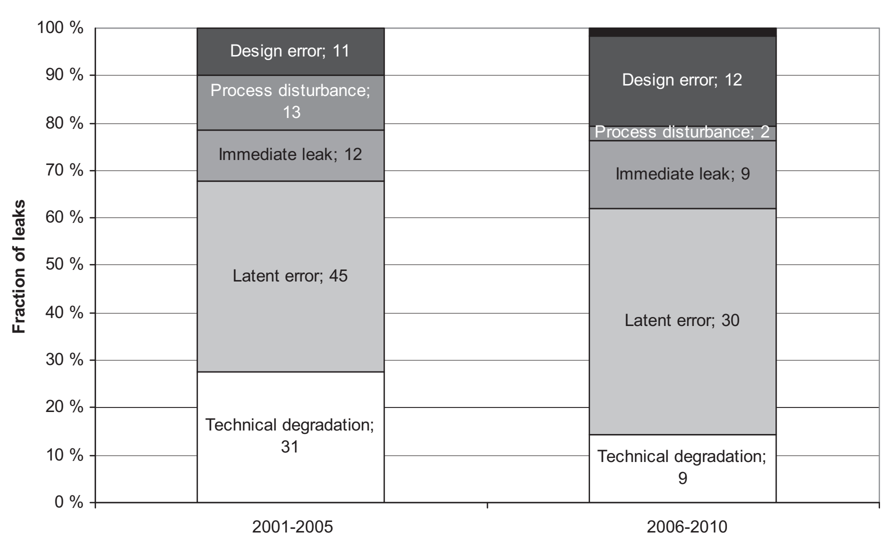

Fig. 2. Hydrocarbon leaks distributed on operational circumstances, average 2001-2010 (n = 175).

lowest number was achieved in 2007, after which a stable, higher level has been reached in the period 2008e2010. In the spring of 2011 PSA requested improved efforts by the industry in order to achieve further reduction.

The source of the data is PSA, but it is important to stress that the reports and investigations are submitted to PSA on a voluntary basis by the oil companies. PSA has permitted analysis of the data, with the proviso that the presentations shall be anonymous. All the raw data from the companies have therefore been available for the analysis. PSA has stated that they encourage analysis of the data, because none of the companies would be able to perform similar analysis, due to confidentiality issues. It could be noted that the statistics is presented without normalization (such as per installa-tion years), as the number of producing installations is very stable from year to year after the year 2000.

The raw data has information about the type of hydrocarbon leaking in the various events. It should first of all be emphasized that only 'production fluids' are included in the statistics, i.e. petroleum products (after refining) such as diesel, hydraulic oil, lube oil, etc. are not included. This is one of the main differences from the leak statistics published by HSE for the UK continental shelf (Edmondson, 2004; Li, 2011). The systems involved are process systems and flowlines downstream of the christmas tree (excluding subsea wells) for production wells, including gas injec-tion and gas lift wells. With respect to type of media in the leaks, the following is the distribution for the period 2008e2010:

- Stabilized oil leak: 9 (21%)
- Oil/gas leak: 3 (7%)
- Condensate leak: 2 (5%)
- Gas leak: 29 (67%)

Two thirds are gas leaks, with stabilized oil as the second main category (21%), whereas oil/gas and condensate are seven and five percent. This could be compared to the distribution reported by Li (2011): Oile24%; 'dual phase'e3%; condensatee4%; gase44%; non-process liquids & othere25%. If non-process liquids and other are excluded, the values show that the leaks in UK are more oil leaks and correspondingly lower number of gas leaks. Li has argued that these percentages are to some extent dominated by the smallest leaks. Since these small leaks are not reported from the Norwegian sector, this may be the explanation of the difference.

Fig. 1 shows that the highest number of leaks occurred in year 2000 and 2002, and that there were significant reduction until 2007. The purpose of the paper is not to analyze in detail the reasons for the decrease in the number of leaks in this period. It should be noted however, that the industry's association (OLF) formulated two campaigns for the periods 2003e05 and 2006e08, each with the target to reduce the 3 year average number of leaks to 50% of the value in the previous three year period. The targets were reached at the end of the first period (in 2005) and in the middle year (in 2007) in the second period. Many experts believe that these reductions were caused by the high focus on prevention of leaks due to these two campaigns. There were no such campaigns earlier, and the new focus was probably a motivation factor for reduction of the number of leaks. Different actions were implemented at the same time in order to improve the quality of the work relating to interventions in the process systems, such as mandatory courses in bolt tightening. A common work permit system was also imple-mented during this period, and training courses were conducted in this regard.

When OLF did not continue the formal campaigns after 2008, this coincided with the increase of the number of leaks. Similar experience occurred in UK a few years earlier, where campaigns were not continued, the number of leaks increased again. A new campaign has been formulated again in 2011, but it is too early to find effects of the new campaign, which is running in the three year period 2011e13.

The development of the approach to main circumstances of the scenarios when the leaks occur on the installations has been document by Vinnem et al. (2007) and Haugen et al. (2011), and the annual trends are documented by PSA. Vinnem et al. (2007) and Haugen et al. (2011) have documented how latent errors have been introduced by different personnel groups involved in the planning, preparation or implementation of manual interventions. Latent errors may result from errors made during planning, if this results in a faulty instruction for the work, such as to open or close the wrong valve. Latent errors are errors that are introduced without being revealed, such as operating the wrong valve or leaving a valve in the wrong position, or tightening bolts in a flange with insuffi-cient torque. When a line or section is pressurized, such as during reinstatement, an open valve may leak instantly, or a gasket may fail due to bolts with insufficient torque. There are many examples of such leaks from the investigations. The classification of leaks that has been used in these works has the following main categories (Vinnem et al., 2007):

- Technical degradation of system (Category A)
- Human intervention
  - *introducing latent error (Category B)
  - *causing immediate release (Category C)
- Process disturbance (Category D)
- Inherent design errors (Category E)
- External events (Category F)

If we split the data in the two five year periods, some changes in the distributions emerge, as shown in Fig. 2. The contribution from technical degradation has been halved in the period 2006e2010, also the contribution from process distributions is significantly reduced. Design errors have increased, and the categories associ-ated with human intervention, especially the latent errors (corre-spondingly to 'delayed leaks').

Work processes are defined in procedures and will usually involve a long list of steps, at least for a complex maintenance or modification task. For our analysis in this study we have structured the work process into four main steps:

1. Planning
2. Preparation
3. Execution
4. Reinstatement

The work process phases are further illustrated in Fig. 9. Plan-ning involves long term and short term planning, including overall schedules, Safe Job Analysis, preparation of the isolation plan, etc. Preparation implies shut down, isolation and depressurization according to the isolation plan, etc. Execution is the completion of the task at hand, the opening of flanges and connections, replace-ments and the remaking of connections. Reinstatement is the resetting of valves and controls according to the isolation plan, as well as the leak testing and starting up.

3. Work process classification of leaks

Leaks on the Norwegian Continental Shelf were analyzed for the period 2001e2005 in the BORA research project. This has been reported in Vinnem et al. (2007) and Haugen et al. (2011) for the period 2001e2005, which was the period with the highest number of leaks in the Norwegian sector, as also demonstrated by Fig. 1. I t

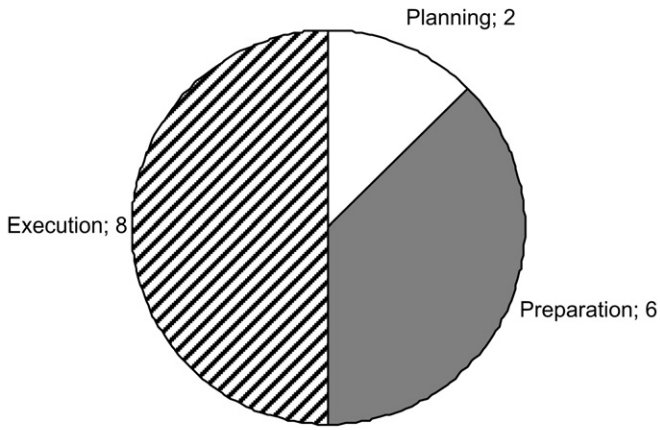

Fig. 3. Distribution of leaks on work process phases, Norwegian Continental Shelf, 2006-10, n = 13.

was therefore considered useful to repeat the analysis for the period 2006-2010.

The model used as basis for the analysis is the risk model developed in the Risk_OMT project, including the work process phases shown above in Section 2. The work process phases are also shown in Fig. 9.

3.1. Leaks on NCS in period 2006-2010

The number of leaks on the Norwegian Continental Shelf in the period 2006-2010 is much lower than in the period 2001-2005, 68 leaks in the last five years versus 125 leaks in the first five years. The leaks that are included in the analysis are those that were associated with manual intervention in the systems (Categories B & C, see Section 2). With this filter, the number of leaks is 57 in the period 2001-2005, and 41 in the period 2006-2010.

Fig. 3 presents the distribution of work process phases were errors have occurred which were causes of the leaks. Only in 13 of the 41 leaks was there sufficient extent of details available in order to allow the work process phases of the errors to be identified. In some of cases, errors were made in two work process phases.

Fig. 4 presents the distribution of personnel categories involved in the errors which were causes of the leaks. Only in 11 of the 41 leaks was there sufficient extent of details available in order to allow the personnel groups that were involved in the errors to be identified. In some of cases, errors were made by more than one personnel category.

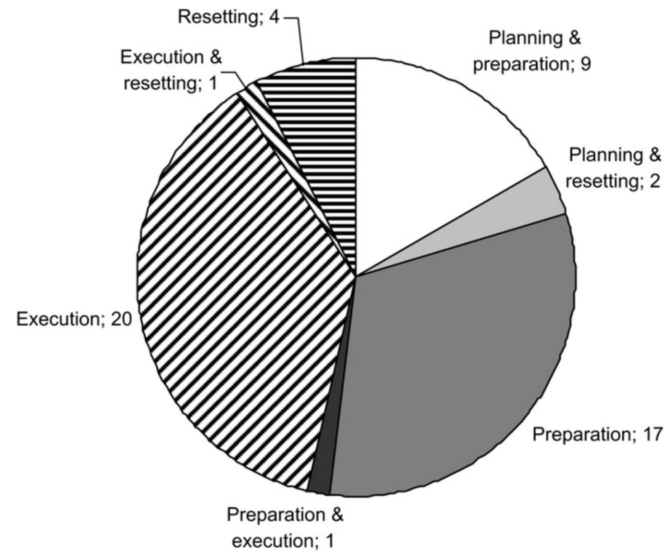

Fig. 5. Distribution of leaks on work process phases, Norwegian Continental Shelf, 2001-10, n = 51.

The personnel groups used in Fig. 4, such as 'Production technician', CCR personnel and 'Area technician' do all belong to the production personnel group, 'area technician' may also be called 'production area responsible engineer'.

It may be observed from Figs. 3and 4 that the distributions do not depart extensively from the corresponding distributions for the period 2001-2005. This is discussed in more detail in Sections 5.5 and 5.6.

3.2. Aggregated data set

By combining the data set for 2006-2010 with data from previous studies, the most extensive data set may be arrived at. The

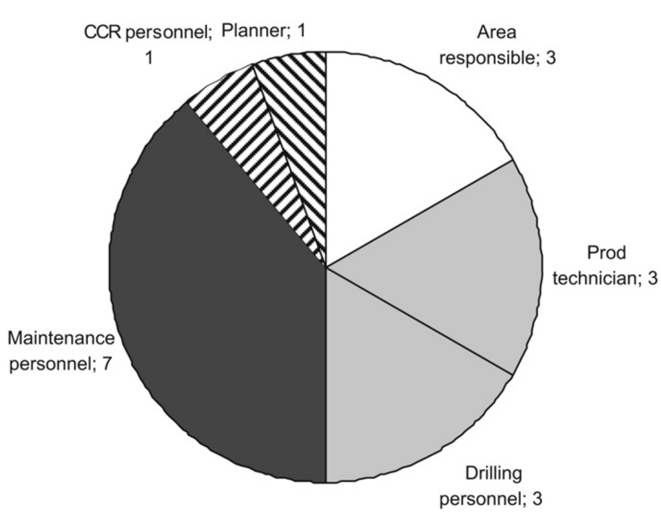

Fig. 4. Distribution of leaks on involved personnel groups, Norwegian Continental Shelf, 2006–10, $n = 11$.

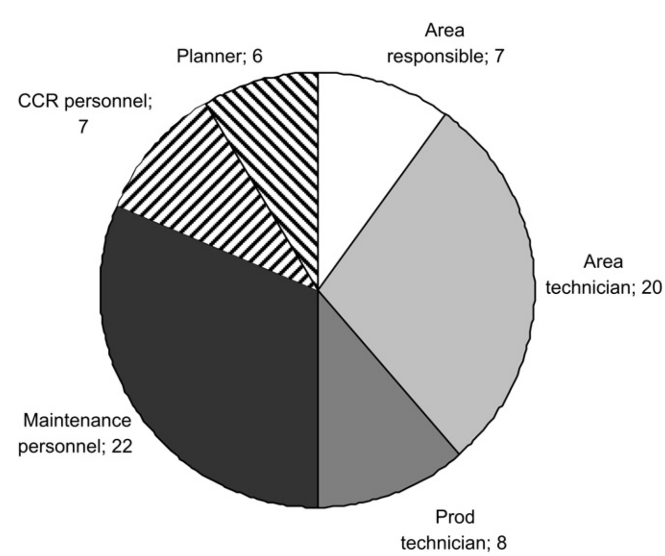

Fig. 6. Distribution of leaks on involved personnel groups, Norwegian Continental Shelf, 2001–10, $n = 49$.

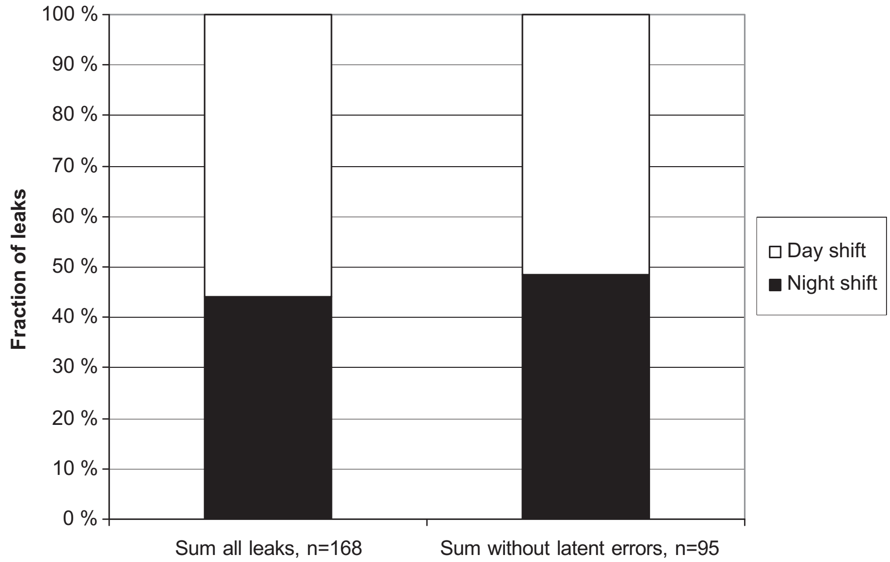

Fig. 7. Relative fractions of shifts when the leaks occur, offshore production installation, Norwegian Continental Shelf, 2001-10, n = 168.

leaks considered here are those associated with manual intervention, categories B & C, see Section 2. The resulting distributions are shown below in Figs. 5and 6. The work process phases were presented in Section 2.

Not surprisingly, the distributions in Figs. 5and 6 are similar to those presented for the individual periods; 2001e2005 and 2006e2010. Preparation and execution are the two main phases. Personnel associated with production operations dominate clearly over maintenance personnel with respect to personnel groups involved in causing the leaks.

4. Time of day when leaks occur

The time of the leak is known in virtually all of the leaks, this is recorded in the reporting system for unwanted events. The analysis of what time the leaks occur is nevertheless not as straight forward as one might expect. It has been demonstrated (Chapter 2) that some of the leaks occur during manual intervention in such a manner that operational failures may introduce latent leak conditions, which unless detected in time, will lead to a leak when that particular section is pressurized.

The important time for these leaks is therefore not the time when the leak occurs, but when the latent error was introduced. The latter is however, not very often known from the investigations. As a rule, we have not been able to determine the time when the latent conditions were introduced in the process system, mainly only the time when the leaks occurred. For the leaks that occur due to latent errors, these times are of limited importance. It may on the other hand be relevant in relation to planning of how to start up a process section after maintenance or inspection.

The database in the current analysis consists of 174 hydrocarbon leaks on the Norwegian Continental Shelf that have been investigated, all leaks exceeding 0.1 kg/s, which is the lower limit of leaks considered to have escalation potential (Vinnem, Aven, Husebø, Seljelid, & Tveit, 2006). The data are available from PSA's Risk Level project (PSA, 2011b), and all the data are presented in an anonymous manner.

Sometimes it may be some uncertainty about whether the time of the leak detection is the time when the leak actually occurred. In general there is some anecdotal evidence about leaks that have continued for hours before detection. But the circumstances of the leaks analyzed in this paper imply that such delays are quite unlikely. The leaks have occurred in the process areas, where the

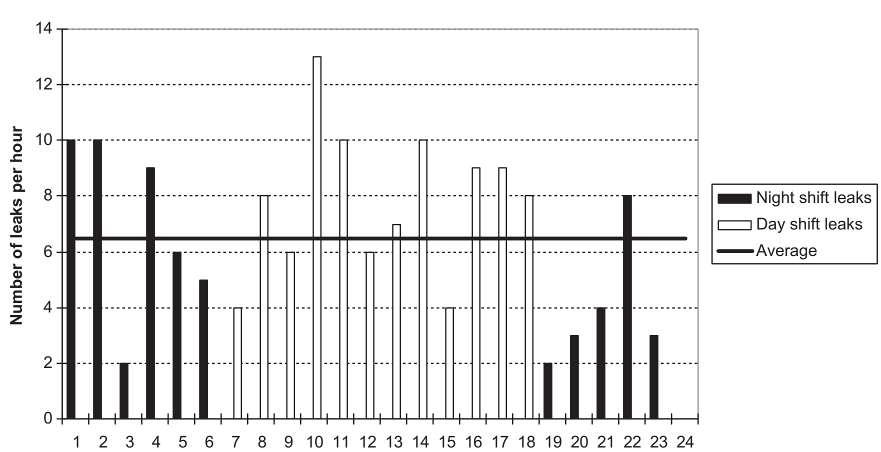

Fig. 8. Hour of the day when leaks occur during day shift and night shift, offshore production installation, Norwegian Continental Shelf, 2001–10, $n = 156$.

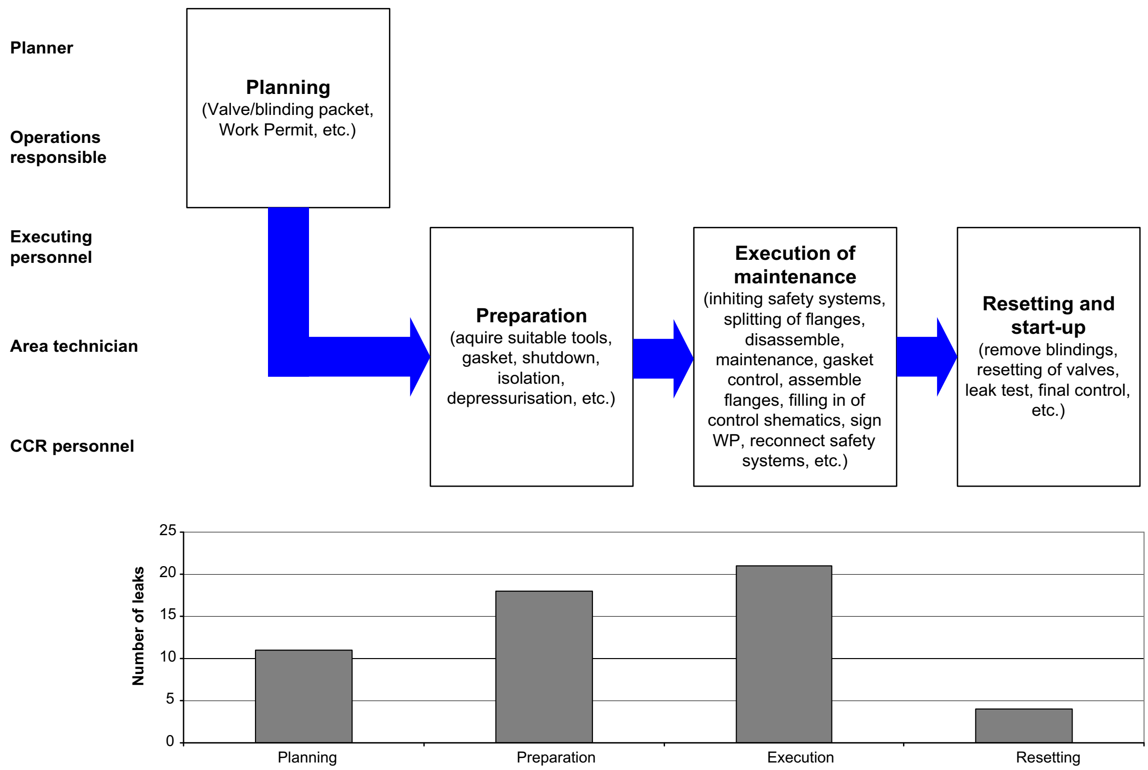

Fig. 9. Illustration of main work process steps and classification of leaks according to main elements of work process, Norwegian continental shelf, 2001-2010, n = 49.

coverage of automatic gas detectors is extensive. The leaks have been substantial, with initial leak rate at least 0.1 kg/s. This implies that gas detectors even at some meters range will be exposed to gas concentration within few seconds. The study is mainly based on accident investigation reports, where aspects relating to delays between occurrence and detection will be discussed. The delays that are considered in the investigation reports are limited to a few cases, and limited to short time, usually up to a couple of minutes, once up to about 15 min. The occurrence times that are discussed in this paper take such delays into account, and the occurrence times have been adjusted for such effects.

The same data are analyzed with respect to the time of the day when they occur. The time is unknown for a few cases, thus the time is known for 168 leaks. The dayshift is interpreted to be from 0700 to 1900, at which time the night shift starts.

Fig. 7 shows that 44% of the leaks occurred during night shift, thus 56% during day shift. One of the main categories of circumstances when the leaks occur is manual intervention, according to Section 2, either as maintenance, inspection or modification. These interventions may introduce latent errors, i.e. errors which will result in a leak when the particular part of the system is pressur-ized, or an immediate leak may be caused, for instance if the wrong valve is opened.

Fig. 7 also has information about the distribution between day and night shift for the leaks, when the latent errors are omitted from the database. The fraction of night shift leaks then increases to 48.4% of the leaks during night shift.

The significance of this is discussed later, but it may be briefly mentioned that PSA Framework regulations (PSA, 2011a) proclaims that night work (between 24:00 and 07:00) is allowed if the risk on the installation is reduced by carrying out the work at night. It would be impossible to argue that having hydrocarbon leaks (which normally results in mustering of personnel to lifeboats) during night implies reduced risk, rather the contrary, because most people will be asleep. Furthermore, if evacuation becomes necessary, that will be more demanding and less safe during darkness. The high fraction of leaks during night is therefore an aspect which calls for improvement.

Fig. 8 presents the distribution of times when leaks occur at the hour of the day for all leaks. 42 of the leaks have occurred during the period 24:00 to 07:00, corresponding to 27%. This implies that that the percentage of leaks is roughly about the same percentage as of the hours included. Consequently, there is no evidence that hazardous work is avoided during the night hours, actually more the opposite, to some degree. Further details are presented in Vinnem (2012).

5. Discussion of findings

5.1. Major hazard precursors versus occupational accidents

Most studies of accident or incident causes and circumstances rely on obtaining the largest possible sample size, it is therefore often considered useful to include as many accidents or incidents as possible. This may be one of the reasons why too often major hazard precursor events and occupational accidents are analyzed together. The present study is to some extent unique, as the number of major accident precursors is more than 170.

Another reason may be the failure to realize that there are extensive differences between accident causation between major hazard precursor events and occupational accidents. This does not necessarily imply that there are different root causes or Risk Influencing Factors (RIFs) involved, competence, training, motiva-tion, awareness, culture, etc. are important RIFs in both types of events. But the risk controls, the possible actions to reduce risk, will be significantly different. Also the time sequences and the intervals may be very different.

Occupational accidents occur more frequently than even major accident precursors, which imply that feedback of experience is achieved regularly without too long delay. In the case of major accident precursors, there may be a long delay between actions that are taken and the feedback with respect to the effect of these actions. The research into accident investigations and the learning from investigations need to take this into account.

We therefore consider it essential to make clear distinctions between major accidents and occupational accidents for the analysis of circumstances and investigations and identification of possible risk reduction actions. The present study is limited to major accident precursors only.

5.2. Robustness of findings

The objective of the work presented in this paper was to analyze in detail circumstances of hydrocarbon leaks on offshore installations in the Norwegian sector for the period 2006e2010. During this work it soon became clear that the data set for this period would be quite limited, such that it would be required to utilize also the data for the period 2001e2005, in order to have a sufficiently large data set.

For the analysis of the time of the day when leaks occur it is considered relevant to use data from the entire period 2001e2010, operational patterns and authority requirements have been mainly unchanged during the entire period, which should make data from the entire period applicable for this analysis. This implies that about 170 leaks are applicable, almost 100 if the latent errors are excluded from the analysis. This is clearly sufficient to make essential observations.

In spite of using all available company internal investigation reports, there are about a dozen leaks where all the variables could be identified from the available documentation for the period 2006-2010. When the entire period 2001-2010 is used, we have about 50 precursor events (leaks) where all the variables could be identified from the available documentation, which is a reasonable data set. In order to make robust observations, this is the primary data set, but possible differences between the entire period and the last five years are addressed and discussed separately.

It is worth pointing out that the analytical approach here does not attempt to identify specific human errors that have been made nor RIFs that have been significant contributors. The approach is limited to identification of circumstances of the activities that have been carried out at the time of the leak. One of the advantages of such an approach is that there is quite limited uncertainty about the classification.

5.3. Why is work process representation essential?

If we consider the investigations of some of the 'famous' process catastrophes during the last 20e25 years, such as Piper Alpha (Cullen, 1990), Longford (Hopkins, 2000), Texas City (CSB, 2007), Deepwater Horizon (Presidential Commission, 2011), it becomes very clear that the outcomes are mainly a result of a long event sequence, which has developed gradually for a significant period, before it comes to a 'point of no return' where control is lost, and emergency preparedness has to take over. During the significant 'build-up' period (sometimes referred to as 'spiral to disaster'), there are usually several opportunities where control might have been regained, if the awareness and understanding of the sequence of events had been sufficiently deep and thorough.

The same may be observed for some of the precursor events that have been extensively investigated, such as the oil leak in the utility shaft (or column) on Statfjord Alpha (Statoil, 2008) and gas leak on Gullfaks Beta (Statoil, 2011).

These event sequences tie closely in with how the normal work on the plants/installations is carried out, this is certainly not limited to how a few safety critical tasks (as lifting heavy loads could exemplify) are carried out. It is therefore essential that the work processes are analyzed, because most of the maintenance and modification tasks have work processes with durations over weeks and months.

Our observations from having conducted such studies over several years are that there is no viable alternative. There are so many important distinctions to be made between different stages of a work process and the different participants in these different stages, that it becomes meaningless to try to find essential obser-vations if not considering the work processes.

It is therefore crucial to analyse the leaks in a work process perspective. A coarse illustration of a work process is shown in Fig. 9, which only shows the main steps in the work process and the involved groups of personnel. Very essential elements of the observations are missed when the leaks are analysed without the work process perspective. It is easy to make unrepresentative observations if the realistic perspective is missing from the analysis.

Fig. 9 demonstrates how the 'sharp end', i.e. the mechanics carrying out the maintenance tasks are not responsible for the dominating contribution to leaks. This point is often missed when the work process representation is not used.

The diagram shows that planning personnel and operations responsible are involved in the planning activities, which contribute with 20% of the errors made. Executing personnel (mechanics, different trade technicians, etc), area (process) technician and CCR personnel are all involved in preparation, execution of maintenance and resetting, with respectively 33, 39 and 7% of the errors.

As far as we are aware, the main efforts by the industry over several years have been limited to actions that may reduce the number of leaks during the execution of the maintenance and inspection work. This is distinctly less than 50% of all the errors made, and may be one of the explanations why the efforts made by the industry has had limited effect.

5.4. Time of leak

The authority requirement to avoid operations that may cause increased risk is quite strong, and has been the same for several years. The analysis in this paper gives no documentation that this has any effect, the proportion of leaks during the prohibited period is about equal to the proportion of hours in that period as a fraction of 24 h.

The findings with respect to shifts when the leaks occur show that the current industry practice in general is not in accordance with the regulations. One probable explanation is that the companies are not aware of the large proportion of leaks associated with preparation. The findings of this paper should be used by the industry to redefine which tasks that may be carried out during night shift, or alternatively change how these tasks are carried out. There are at present far too many leaks that occur during night shift, especially in the prohibited period between 24:00 and 07:00. This is further discussed in (Vinnem, 2012).

The data basis for this part of the study is substantial, and it could not be argued that the findings in this part are particularly uncertain or unrepresentative.

5.5. Work process phases

The importance of representing the work process phases has already been discussed in Section 5.3. The available data is more limited for this part of the study, and a thorough evaluation of the robustness of the findings is required.

The total number of leaks in the period 2001-2010 for the entire Norwegian sector is 175 leaks with flowrate exceeding 0.1 kg/s. Leaks associated with manual intervention (categories B and C, see Section 2) are the primary focus in this analysis. The leaks in these two categories are fewer, 96 leaks in the period 2001-2010. In about half of these incidents are all the relevant details available.

When data from the two periods 2001-2005 and 2006-2010 are compared, it can be observed that the general patterns are quite similar. These similarities imply obviously that also Fig. 5 will be quite similar. It can therefore be observed that even though the number of leaks is considerably lower in the period 2006-2010, the distribution of errors in the different work process phases is virtually unchanged.

With the close similarity between Figs. 3and 5, it is most representative to use Fig. 5 as the main message. Fig. 5 is based on 51 leak events, and has the most robust basis. The following approximate fraction may be observed from Fig. 5:

* Planning; one in five (20%)
* Preparation, one in three (33%)
* Execution, one in two and a half (40%) e
* Reinstatement, one in fourteen (7%)

The distribution on work process phases is important for the industry to observe when identifying risk reduction actions. It has been a tradition that the main efforts have been directed at the execution phase and the mechanics that carry out most of the work in this phase. But at least 50% of the errors are made in other phases, most dominantly in the preparation phase, where the trade mechanics have a limited involvement.

5.6. Involved personnel categories

There is an obvious correlation between work flow phases and involved personnel groups. It has been assumed implicitly for a long time that maintenance and modification personnel (mechanics) was virtually the only group involved in these precursor events. It is quite obvious from the present analysis that the picture is very different from this far too simplistic view.

With respect to the relationship between the two main groups, maintenance personnel and production personnel, Figs. 4 and 6 show similar relationships. Fig. 6 is based on 49 events, and may be considered to have a robust basis. The following approximate fraction may be observed from Fig. 6:

* Area responsible, area technician, production technician; one in two (50%)
* Maintenance personnel; one in three (31%)
* Control room personnel; one in ten (10%)
* Planning personnel; one in twelve (9%)

If area responsible, area technician, production technician and control room personnel are considered as one group (production personnel, usually oil company employees), their contribution is about twice as high as the contribution from maintenance and modification personnel, whereas the common belief is that maintenance and modification personnel (often contractor personnel) is virtually the sole group making these errors.

The sum of error cases in Fig. 6 is 70 corresponding to 49 precursor events; this implies that the average number of errors per leak event is close to 1.5 errors per leak.

6. Conclusions and recommendations

The paper has documented extensively why it is important that analysis of hydrocarbon leaks as major hazard precursors should be based on a work process representation.

When a work process representation is chosen, there has to be a clear distinction between major hazard precursors and occupational accidents, because the work processes that are relevant for major hazard precursors do not cover at all the activities that may cause occupational accidents to occur and vice versa.

Night shift is not underrepresented in statistics of time of leak, in spite of Norwegian regulations prohibiting hazardous work between 24:00 and 07:00. This paper has documented a high number of hydrocarbon leaks during night shift, and in particular in the prohibited period 24:00 until 07:00. Even if only leaks associated with manual intervention (where the leak could have been avoided if the activity had not been performed during night shift) are considered, there is still a high number of leaks that occur in the prohibited period.

The paper has demonstrated that tasks relating to preparation for maintenance and modification have more leaks during night shift compared to day shift. As far as what is known, it has been considered by the petroleum industry that preparation is virtually a hazard free activity. The paper has demonstrated clearly that this is not the case. Preparations for maintenance and modifications need to be banned completely by the oil industry on night shift, in order to operate in accordance with applicable Norwegian legislation.

From the point of preventing hydrocarbon leaks, the paper has shown that planning, preparation and reinstatement are more important than execution. Yet the industry has until now focused almost all its attention on the execution of maintenance and modification tasks. As a consequence of this, the production personnel have twice the contribution as the contribution from maintenance and modification personnel. The production personnel are mainly employees of the oil companies, rather than contractors who have often received more attention that what is justified by the results of the present analysis.

The paper has been based on access to investigations (or ’in depth’ studies similar to investigations), still the relevant details were only available in about half of the incidents, when leaks associated with human intervention are considered. It would have been more data available if the investigations had a stronger focus on identification of work process phases where errors occurred and the type of errors and potential causes. It is known that the industry in 2012 has started to focus on these aspects in internal reporting. Thus better data should hopefully be available in the future.

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